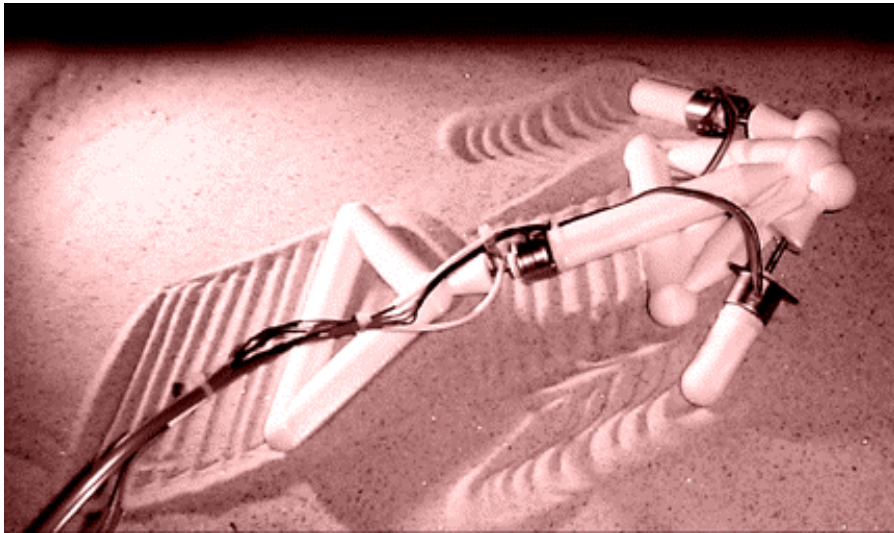# Self-designing machines

A response to a request for information on advanced concepts and technologies for
Human/Robotic exploration of the Solar System

Hod Lipson
Mechanical and Aerospace Engineering and
Faculty of Computing and Information Science
Cornell University, Ithaca, NY 14853
HL274@cornell.edu   607 255 1686

Figure 1. Locomoting machine synthesized by an evolutionary process[1]

ROBOTS ARE TRADITIONALLY PRE-DESIGNED machines, whose physical architecture and functional behavior has been preconceived by a human designer. Advance manual design, however, becomes difficult and risky because of the impossibility of foreseeing the problems a robot in a long-term expedition will have to solve. This indefiniteness overwhelms the flexibility that has been traditionally afforded by ideas of adaptive control and reconfigurable morphology. This white paper aims to outline the need to seek novel methods for making machines that can fully redesign themselves – both morphology and control – at a much higher level, to accommodate unknown tasks in unknown and changing environments where the scope of solutions cannot be pre-specified by a designer in advance.

The vision

What are the scenarios under which self-designing machines would be used in space exploration? It is likely that an astronaut in deep space exploration will have far less design capabilities, in terms of manpower and experience, and far less fabrication

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[1] H. Lipson and J. B. Pollack (2000), "Automatic design and Manufacture of Robotic Lifeforms", *Nature* 406, pp. 974-978

capacity, in terms of facilities and material, than are available to a team of engineers on earth. Moreover, it is likely that the kind of problems that such an astronaut will face will become less intuitive as new strange environments and realities with unfamiliar physical conditions are encountered. In preparation for those circumstances, it is necessary to develop new automated design and fabrication systems, that can automatically design, fabricate and test new robotic machinery in whatever reality they encounter, while recycling material and learning from their experience. A single crew of astronauts will not have the capacity to deal with this manually, and help from earth will be impractical. Long before fully automated design and fabrication will be available, a more primitive version that can automatically deal with simple and mundane design tasks will also be valuable, by freeing the human to deal with higher-level design.

The reality

Concepts of design automation and flexible manufacturing have been goals of engineers for many years. Typically, methods developed are focused essentially on parametric optimization, where the parameters of the problem and its architecture are manually pre-specified and automation is applied to refine or solve parameter sets. Although such problems are often very hard and constitute a difficult computational challenge, they do not address the problem of open-ended design and unconstrained manufacturing. In an open-ended problem, more and more parameters and building blocks can be added, and at the same time manufacturing constraints are reduced, making the overall problem exponentially complex and potentially intractable.
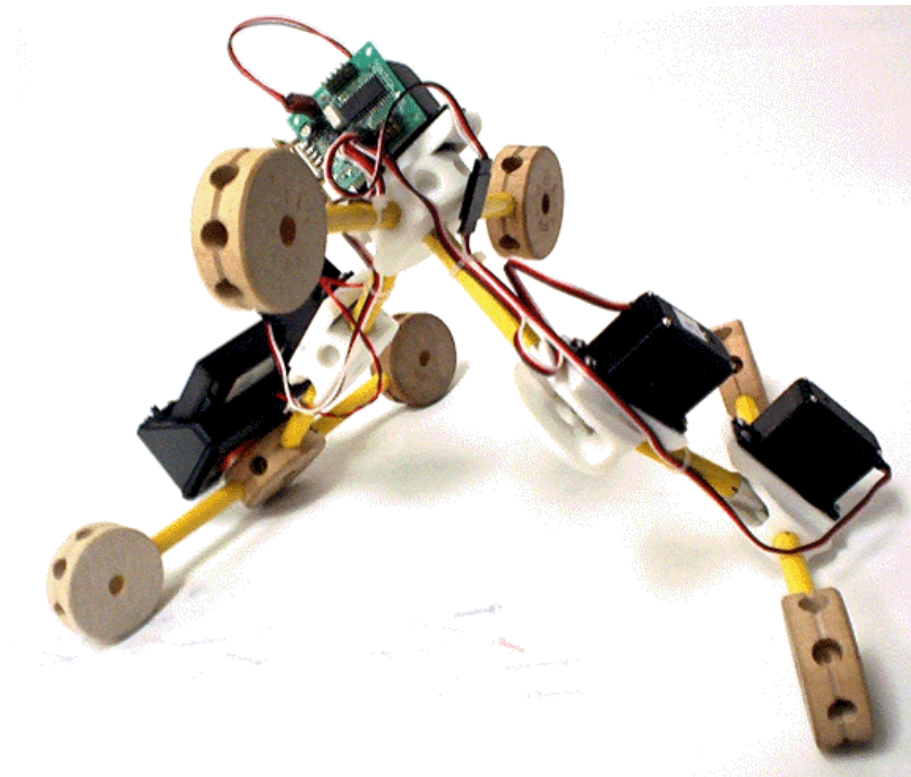
Figure 2. Modular robot designed by an evolutionary process and grammatical encoding[7]. Note reuse of a "T-Junction" module.

Is it possible to automated open-ended design, to make a machine that can design other machines, or portions of itself, to achieve arbitrary tasks? We have two proofs of existence: Nature, and Mankind. Natural systems have evolved over billions of years to produce machines in response to arbitrary challenges. Similarly, human engineers are capable of designing and fabricating machines that solve arbitrary tasks. We must think of an engineer not as a single person, but as a collective of people, engineering knowledge and technological tools, that together have also evolved over centuries and passed information from generation to generation, encountering new problems in new environments. And so it seems that both these proofs of existence – Nature, and Engineering man – are essentially self-organizing systems that give rise to complex machines in response to a long chain of challenges provided by their environment. Can we emulate this process computationally, and then implement it in a physical machine?

Over the last several years I have been studying computer-aided design, self-organizing and evolutionary processes as the key to future fully automated design. Inspired by the works of Karl Sims[2], and a wealth of new ideas in Evolutionary Robotics[3], Evolutionary Computation, Co-evolutionary dynamics[4], Evolutionary Hardware[5] and Artificial Life[6], we embarked on the GOLEM project[7]. The goal was to develop processes that can automatically design and fabricate complex machines in physical reality. We have combined ideas of evolution and self-organization together with rapid prototyping technology to make the first physical machines that were designed and fabricated with almost no human intervention[1]. Figure 1 shows one of these machines, which were evolved to locomote over a flat terrain. The process was given a simulator for the physics of three types of building blocks (bars, motors, and neurons), a list of how these building blocks can connect to each other, and a fitness criterion measuring net distance traveled. Starting with a population of 200 blank machines, this one resulted after 300 generations. More recently, we have extended the complexity of evolved machines by evolving not just the design but also a grammar that describes how to construct them systematically[8]. One of these robots is shown in Figure 2. Note that the design process has discovered a "T-Junction" module and has used it three times in the design of this robot. This is the beginning of a design process that can scale to higher complexities.

Required Technologies

Self-designing machines are part of a long-term vision that might mature into a practical level in 2-4 decades, and will provide second-order support for any long-term endeavor. However even now, following the very preliminary results outlined above, it is possible to identify three technologies that need focused research to make this vision a reality.

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[2] Sims, K. (1994). Evolving 3d morphology and behavior by competition. In Brooks, R. and Maes, P., editors, Proceedings 4th Artificial Life Conference. MIT Press

[3] Nolfi S., Floreano D. (2000), Evolutionary Robotics – The Biology, Intelligence, and Technology of Self-Organizing Machines, MIT Press, Cambridge

[4] Hillis, D. (1992). Co-evolving parasites improves simulated evolution as an optimization procedure. In C. Langton, C. Taylor, J. F. and Rasmussen, S., editors, Artificial Life II. Addison-Wesley, Reading, MA

[5] NASA/DOD Evolutionary Hardware conference: Http://cism.jpl.nasa.gov/ehw/events/nasaeh01/

[6] C. Adami (1998), Introduction to Artificial Life, Springer Verlag

[7] Http://demo.cs.brandeis.edu/golem

[8] Hornby, G. S., Lipson, H. Pollack, J. B. (2001). Evolution of Generative Design Systems for Modular Physical Robots. IEEE International Conference on Robotics and Automation

The necessary technological foci for this vision are

1. **Scaling evolutionary robotics into higher complexities.** Finding ways to allow evolutionary robotics to scale from designing robots for toy problems to robots tasks of higher complexities. How can a mutation-selection process reach high complexities? This *scaling* problem is controversial in biology too ("the missing link"), but there is growing evidence for the importance of mechanisms for discovery of intermediate stable states that constitute useful building blocks for higher levels, composed in a hierarchical fashion.

2. **Full function freeform fabrication** Like Star-Trek's "Replicator", or the nano-fabrication facilities of the Diamond Age[9], there is a need to devise the technology that can fabricate arbitrarily complex machinery, including both control and morphology, without intervention. The predecessors of this technology are the currently available rapid-prototyping machines.

3. **Machine Recycling.** Any long term expedition will have very limited resources at its disposal. Just as water and air need to be recycled in even short term expeditions, so do materials and robot supplies need to be recycled efficiently in any longer term expedition, to allow for making new machinery. Methods for recycling machinery at a very low level are required.

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[9] Neal Stephenson , (2000), *The Diamond Age*, Bantam Doubleday Dell Pub

Self-designing machines

Technology that allows robots to re-design and re-fabricate machines for new tasks in new environment.
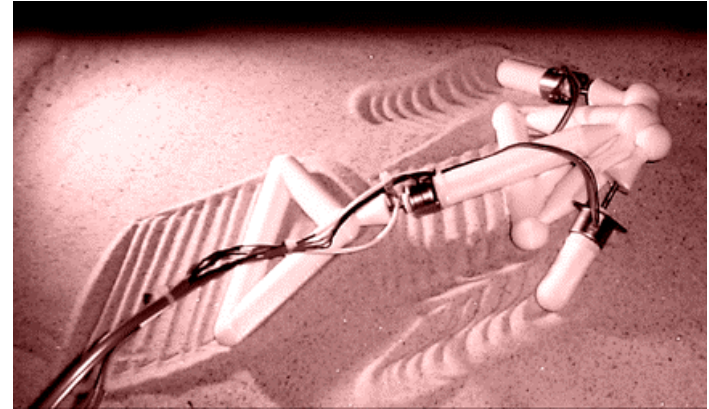
Research required in advancing and scaling technologies in the area of

- Evolutionary Robotics
- Freeform manufacturing

For videos see

Http://www/mae.cornell.edu/lipson